

Optimization of mixing time to improve the quality of broiler feed using ferromagnetic microtracers

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ABSTRACT

The efficient production of feed for broiler chickens faces the challenge of achieving homogenous and stable mixtures, as the lack of uniformity may compromise the nutritional quality and profitability of the final product. In this context, mixing time is a crucial factor influencing both blend homogeneity and moisture content, essential parameters to ensure the feed quality. This study evaluated the effect of five mixing times (60, 90, 120, 180, and 210 s) on uniformity and moisture percentage of the broiler feed using ferromagnetic microtracers and advanced statistical analysis. Homogeneity was assessed using the coefficient of variation (CV) and the Poisson distribution, whereas moisture content was analyzed using non-parametric tests. The results showed that intermediate mixing times (120 and 180 s) resulted in homogeneous mixtures (CV < 10%), in contrast to the shortest and longest durations, which exhibited greater variability. Although the Kruskal–Wallis test revealed significant differences in moisture content across different mixing times, Spearman's correlation suggested no direct, linear relationship between mixing time and moisture. These findings underscore the importance of establishing an optimal mixing duration, particularly in the range of 120 to 180 s, to enhance feed quality, improve process efficiency, and reduce production costs, thereby contributing to the sustainability of the poultry industry.

Keywords: Mixing time, Moisture, Coefficient of variation, Feed, Product quality.

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1. INTRODUCTION

Globally, feed production amounts to approximately 1 billion tons per year (Syrovatka et al., 2019; Thomas and van der Poel, 2020). Over the past decade, the consumption of poultry products, especially chicken meat, has grown significantly worldwide. This increased demand has strengthened chicken meat's global production share, rising from 15% to 30% (Adusei-Bonsu et al., 2021). This context presents significant challenges in terms of sustainability and efficiency, especially in terms of feed production, which accounts for 60% to 70% of production costs in the poultry sector (Syrovatka et al., 2019; Zentek and Goodarzi Boroojeni, 2020; Poholsky et al., 2021). This high cost of animal diets reflects increasing pressure on the availability and quality of raw materials, where feed must ensure a safe and nutritious supply (Adusei-Bonsu et al., 2021).

In this context, guaranteeing quality and efficiency in technical processes, such as mixing, is crucial to optimize operational parameters and ensure a high-quality feed. Various factors directly influence the quality and uniformity of the mixture for feed production. Among the most relevant are the particle size and shape ingredient incorporation order, density of each component, mixing time, and formulation (Astankulov et al., 2024). The main characteristic of the mixing process is its homogeneity (Mansour et al., 2020), which involves achieving a random distribution of ingredients throughout the mass (Rocha et al., 2022) within minimal time and energy consumption to maximize process efficiency (Sakhno et al., 2018; Mansour et al., 2020) and nutrient utilization. A common practice that affects process efficiency is excessive mixing time, which not only leads to unnecessary energy and resource consumption but can also negatively impact feed quality, causing degradation of vitamins, additives, and medications (Syrovatka et al., 2019; Sakhno et al., 2020). This can lead to a reduction in the final product quality and, consequently, to significant economic losses for feed

manufacturers.

Pellet quality is intrinsically linked to moisture distribution and management during critical stages of the production process. According to Thomas and van der Poel (2020), proper conditioning not only facilitates moisture diffusion into particles but also improves compaction. In this context, initial moisture content levels and the ability of particles to hydrate uniformly significantly influence the formation of durable and homogeneous pellets. An increase in moisture content during conditioning, within the range of 30–40 g/kg, contributes to reduced variability in final pellet quality. These findings reinforce the importance of precise moisture control, as uneven moisture distribution can compromise both the structural integrity and durability of the pellet, which are critical for storage and handling.

Recent studies have examined the effect of mixing time on mixture homogeneity and moisture retention in feed. Bratishko et al. (2020) demonstrated that mixing time is a determining factor in mixture heterogeneity and moisture distribution in the final product. As mixing time increases, variability in mixture and moisture content decreases, emphasizing the importance of precise control of this parameter to obtain a uniform mixture. These findings align with the results of Ansuree et al. (2021), who explored how mixing time and speed affect homogeneity in mixtures with varying particle sizes. Their experiments determined that a mixing time of 4 to 6 min at 75 rpm can achieve a coefficient of variation (CV) of less than 10%, representing an adequate level of homogeneity to meet quality standards in the feed industry. These studies reinforce the relevance of optimizing mixing parameters to ensure a uniform and high-quality product, especially in diets for growing poultry.

Rubio et al. (2023) proposed that shorter mixing times, approximately 60 s, do not significantly affect growth performance or body weight uniformity in poultry at advanced growth stages. The researchers suggested that reducing mixing time could optimize resources without compromising feed quality. However, the optimal mixing time remains a variable without consensus, highlighting the need to establish precise parameters that not only ensure mixing homogeneity but also optimize moisture content and product stability during shelf life.

Despite advances in understanding the impact of mixing time, the precise relationship between mixing time and final product moisture content remains largely unexplored. Bratishko et al. (2020) emphasized that, although mixing time influences mixture homogeneity. Few studies examine how this parameter affects moisture content and consequently, the stability of feed during storage. Pellet quality significantly depends on its moisture content. Elevated level can lead to spoilage, while insufficient moisture reduces palatability and digestibility (Yermukanova et al., 2024). This parameter is also essential for calculating nutritional indices and evaluating overall feed quality (Huang et al., 2022). Moisture imbalance can, in many cases, be associated with inadequate control in the previous stages of manufacturing. Zentek and Goodarzi

Boroojeni (2020) emphasize the importance of properly managing hydrothermal process variables, such as temperature and water addition to avoid compromising product quality.

The study aimed to evaluate the optimal mixing time by analyzing the coefficient of variation in the homogeneity of the mixture. Additionally, it will examine how mixing time impacts the moisture percentage of the final product. This comprehensive approach will not only optimize resource use in the industry, reducing costs and improving product quality, but will also provide a scientific basis for continuous improvement in mixing processes, aiming to produce high-quality feed.

2. MATERIALS AND METHODS

2.1 Study Area

The research was conducted at an agroindustrial facility dedicated to the production of feed, located in the province of Chimborazo, Ecuador. The facility operates in a region with an average annual temperature of 15°C and a relative humidity of 70%, conditions that do not significantly influence its industrial processes.

The production line under study is dedicated to feed production for broilers in the growth stage, produced in two forms: crumble and pellet. The crumble form is a crushed or broken presentation in uneven shapes ranging in sizes from 1.5 to 3.1 mm. The pellet form consists of compacted cylinders with dimensions of 6 mm in length by 4 mm in diameter, the latter form does not undergo a crushing process. These characteristics ensure palatability, digestibility and availability of essential nutrients for animals.

2.2 Sample collection

Prior to sample collection, 50 g of ferromagnetic microtracers were added per ton of mixture as a marker to assess homogeneity. Each milligram of microtracers contained 25 iron particles, enabling accurate quantification based on the guidelines from the manuals "Microtracer F Testing for Completeness of Mix" and "Quantitative Assays with Microtracers F" (Micro-Tracers Inc, 2013).

Fourteen samples of approximately 100 g each were collected at the discharge hopper of a horizontal paddle mixer (Jiangsu Zhengchang brand, SSHJ 2nd series, 1-ton capacity). Samples were taken at five different mixing times: 60, 90, 120, 150, 180, and 210 s. For each time, 14 samples were uniformly extracted distributed during the operation, totaling 70 samples. The choice to collect fourteen samples per time point was supported by the works of Bernotas (2012) and Knarr (2023), who recommend collecting at least 10 samples to adequately assess homogeneity through the CV.

To evaluate the moisture percentage of the final product, the number of samples per batch ($n = 7$) was determined in

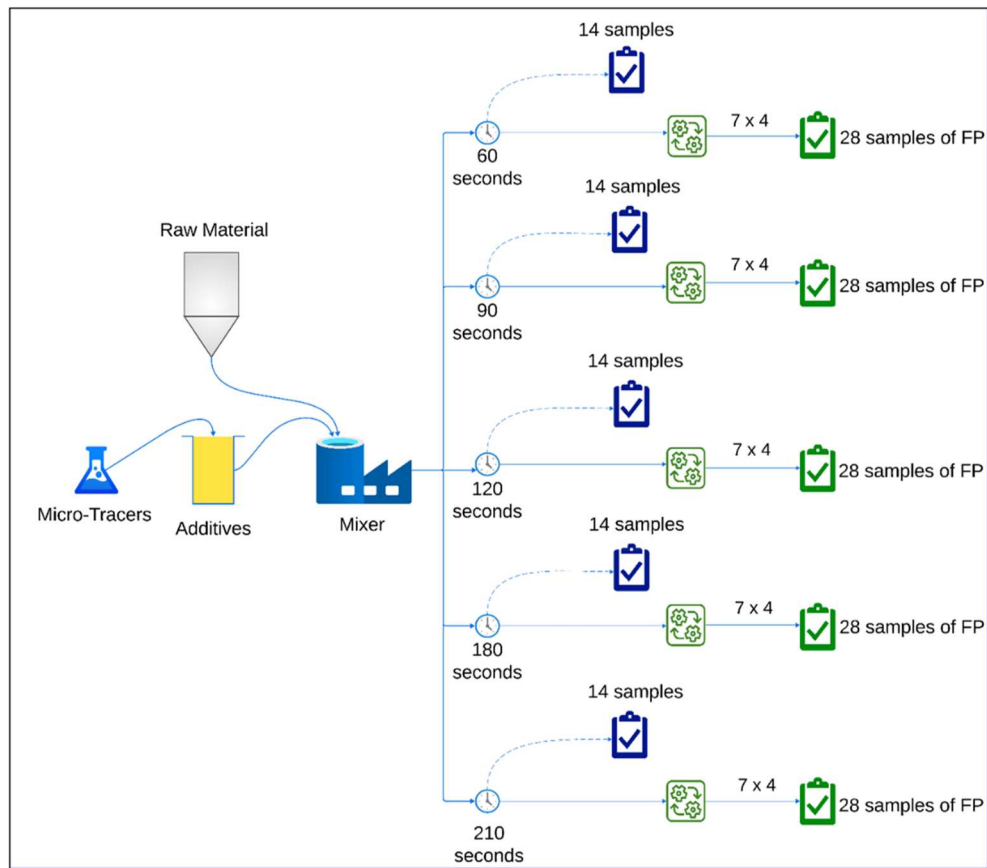


Fig. 1. Process diagram and number of samples to determine CV and % Moisture of final product.
Note: FP, Finished Product.

accordance with the international standard ISO 3951-1:2005 (International Organization for Standardization, 2022), based on a lot size of 25 sacks, inspection level III, and an AQL of 1.5%. Each of these 7 samples was analyzed in four independent replicates, following the company’s internal Good Laboratory Practices (GLP) as outlined in the Standard Operating Procedure (SOP) titled “Final Product Release”. At total 28 samples were analyzed per production batch (1 ton) at each mixing time.

Each sample was analyzed using a gravimetric thermobalance (Radwag model MA210.X2), with 3.5 g of product per analysis. According to national regulations and the quality standards adopted by the company, the maximum moisture limit allowed in the final product is 13% (Instituto Ecuatoriano de Normalización, 2014). Fig.1 shows a simplified representation of this process.

2.3 Experimental Design

A completely randomized design (CRD) was used in the study to evaluate the effect of mixing time on two key variables in feed for growing broilers: the homogeneity and the percentage of moisture content in the final product. The experimental factor considered was mixing time, which was evaluated at five levels: 60, 90, 120, 180, and 210 s.

Each level of mixing time represented a production batch,

produced under controlled conditions that included conditioning temperature (80°C), steam pressure (30 psi), particle size in the mix (573 μm), ambient humidity (~ 60%) and mixer speed (46 rpm). These conditions were maintained constant to ensure that any observed variation in response variables could be attributed solely to mixing time. These conditions were maintained constant to ensure that any observed variation in response variables could be attributed solely to mixing time.

These operating conditions were selected based on prior production trials conducted at the facility where the study was carried out, which demonstrated consistent and acceptable performance under its specific machinery setup, automation level, and diet formulation. Similar parameters have been reported in the literature: Yermukanova et al. (2024) used a conditioning temperature of 80°C and ~58 psi, while Oliveira et al. (2022) operated at 82°C and 1.5–2 bar (21.7–29 psi), supporting the validity of the conditions applied in this study.

For the formulation of the feed, a standard recipe designed to meet the specific nutritional requirements of growing broilers was used. The formulation included a precise mix of raw materials and additives, as detailed in Table 1 of the study. This approach ensures that the ingredient composition does not interfere with the results

obtained.

The combination of these experimental procedures allowed for a comprehensive analysis of the effects of mixing time on feed quality, considering both the homogeneous distribution of the components and the stability of the final product in terms of moisture content.

Table 1. Formula (per ton) for the elaboration of balanced feed for broilers in the growing

Bulk raw materials	Weight (kg)	%
Yellow corn	302.00	30.20
Soft wheat	220,00	22.00
Soybean paste	178.00	17.80
Rice powder	160.00	16.00
Wheat bran	110.00	11.00
Calcium Carbonate	15.20	1.520
Raw materials additives	Weight (kg)	%
Monocalcium phosphate	6.80	0.68
Salt	3.10	0.31
Vitamin and mineral premix	1.50	0.15
Mycotoxin binder	1.00	0.10
Yellow dye	0.95	0.095
Antifungal acid	0.75	0.075
Enzymes	0.50	0.050
Antioxidant	0.20	0.020

2.4 Statistical Analysis

The statistical analysis focused on evaluating mixture homogeneity and the relationship between mixing time and final moisture percentage in feed for broilers. To determine mixture uniformity, the ferromagnetic microtracer method, a widely recognized technique in the feed manufacturing industry (Bernotas, 2012; Syrovatka et al., 2019). CV and CV-Poisson, key metrics for measuring the relative dispersion of particles in the samples, were calculated, serving for measuring the relative dispersion of particles in the samples (Rubio et al., 2023). Statistical significance for the tests was set at $p < 0.05$.

Mixing uniformity is commonly quantified using (Knarr, 2023), a parameter that expresses the ration between the standard deviation and the mean of particle distribution. This indicator was established as the primary metric, considering values below 10% as acceptable according to manufacturing standards (Adusei-Bonsu et al., 2021; Poholsky et al., 2021; Knarr, 2023; Rubio et al., 2023). A Poisson distribution model is assumed when dealing with particle count data, wherein the mean and the variance are equal. The CV-Poisson is calculated as the standard deviation divided by the mean, expressed as a percentage. (Thiex et al., 2019; Sakhno et al., 2020). The CV-Poisson was used as theoretical reference to differentiate between random variation (indicative of homogeneity) and non-random heterogeneity. According to Thiex et al. (2019), a CV, referred by the author as relative standard deviation (RSD), that exceeds the CV-Poisson is interpreted as uniformity insufficiency, whereas similar values suggest a

homogenous blend characterized by inherent random process variability.

Additionally, a Chi-square goodness-of-fit test was conducted to verify whether particle distribution at each mixing time level corresponded to the expected distribution under the Poisson model. A p -value > 0.05 was accepted as evidence of a uniform mixture, whereas a p -value < 0.01 was interpreted as indicative of an insufficient or incomplete blend. However, given that some expected frequencies were low, the Monte Carlo simulation technique was used to increase the robustness of the statistical analysis. This technique enabled the generation of adjusted p -values through random simulations, improving the accuracy in evaluating discrete data and ensuring a reliable interpretation of the results.

To investigate the possible relationship between mixing time and moisture retention in the final product, an exploratory data analysis (EDA) was performed, followed by Spearman's correlation analysis. This non-parametric analysis helped identify whether there was a significant trend between these variables, with a significant correlation indicating a direct relationship between mixing time and the feed capacity to retain moisture. To evaluate differences in moisture distribution across mixing times and after confirming the normality absence (Shapiro-Wilk, $p < 0.05$), differences among mixing durations were analyzed using the Kruskal-Wallis test. Upon detecting a global significance ($p < 0.001$), Dunn's post hoc comparisons with Bonferroni adjustment were performed to control for Type I error in multiple comparisons.

In combination, these statistical methods ensured a comprehensive and detailed analysis, providing quantitative evidence to understand how mixing time affects feed quality, both in terms of homogeneity and stability of the final product. The statistical analysis and graphical visualizations were conducted using R software version 4.3.3, specifically within the RStudio environment. This involved utilizing the following R packages: `dplyr`, `tidyr`, `ggplot2`, `FSA`, `patchwork`, and the core stats package.

3. RESULTS

3.1 Determination of Optimum Mixing Time

The results of the analysis of mixing times and their influence on the homogeneity of the mixture are shown in Fig. 2. The p -values obtained for mixing times of 60, 90, and 210 s (all below 0.05) indicate that the particle distribution does not follow a Poisson distribution, suggesting non-homogeneous mixture. At these times, the high CV values, reaching up to 15.95% for the 210-s time, reinforce the notion of a mixture with significant variability. In particular, the 90-s time presented a CV of 14.76%, indicating a considerable dispersion of the particles and a lack of uniformity in the mixture.

In contrast, for the 120 and 180 s times, the p -values were greater than 0.05, indicating that the particle distribution is

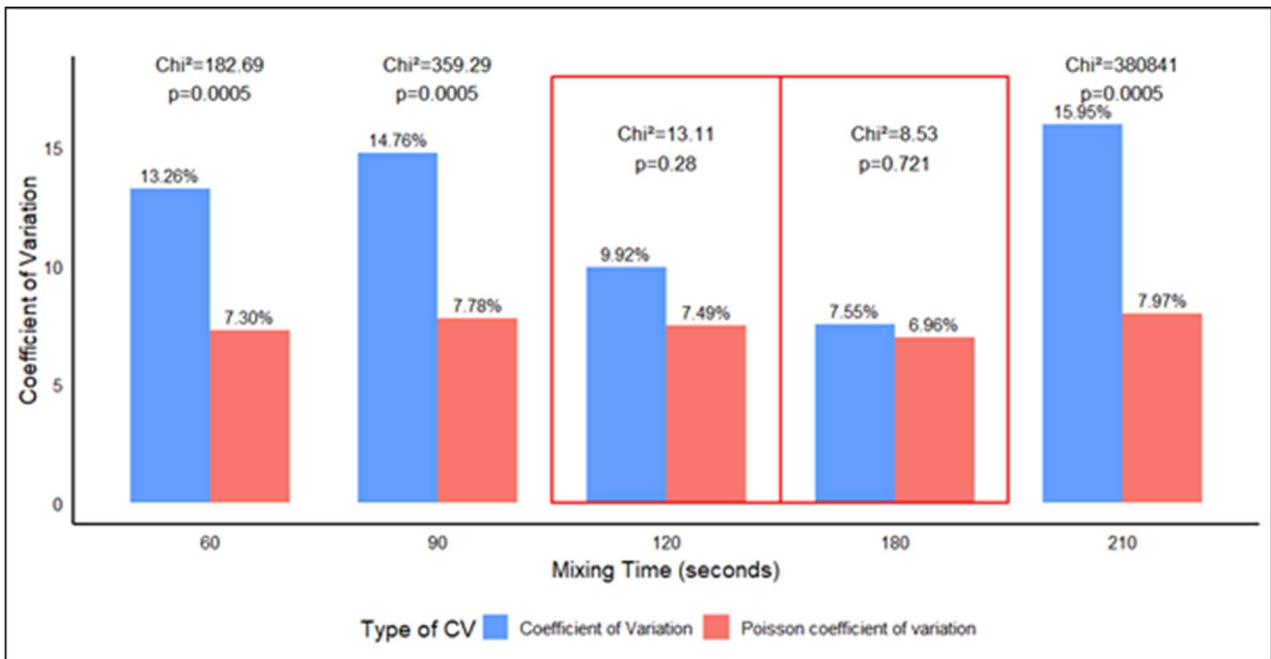


Fig. 2. Coefficients of variation (CV and CV - Poisson) by mixing time. Note: Monte Carlo data simulation was used to run the Chi-square test to avoid the expected frequency restrictions, RSudio software 2024.09.01

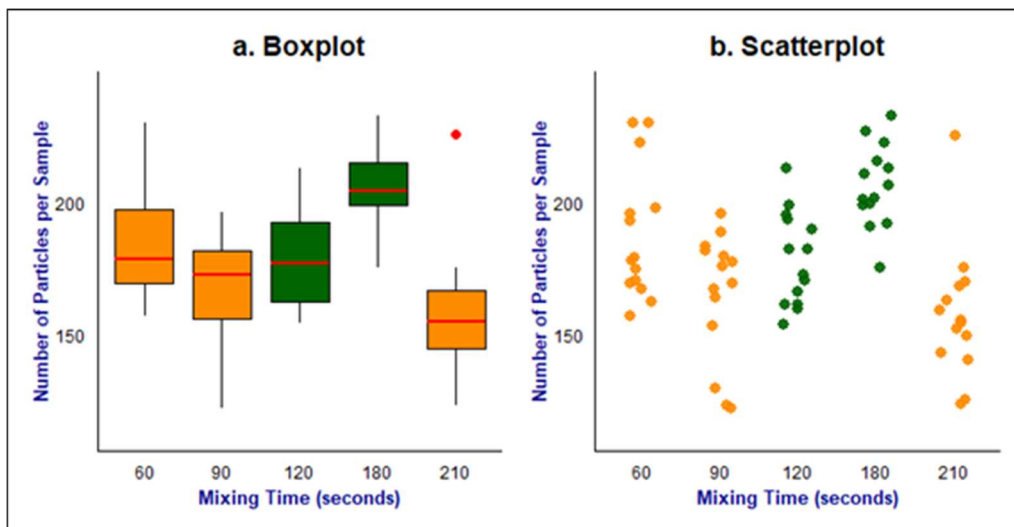


Fig. 3. (a) Box and (b) scatter plots of ferromagnetic particles for each mixing time.

consistent with a Poisson distribution, suggesting a homogeneous mixture. In these cases, the CV values were significantly lower, 9.92% for 120 s and 7.55% for 180 s, indicating a better distribution of particles in the mixture. This suggests that, at these times, the particles are more uniformly distributed, improving the homogeneity of the mixture.

Fig. 2 illustrates the CV and CV-Poisson values for each mixing time. The CV values are consistently higher than the CV-Poisson values, reflecting a greater sensitivity of the CV to extreme variations in the sample. For mixing times 60, 90 and 210 s, the difference between these two coefficients is

especially notable, reinforcing the presence of extreme variability in the mixture. For mixing time of 120 and 180 s times, the difference between CV and CV-Poisson values decreased to 2.43% and 0.59%, respectively. This behavior indicates that, as the mixing time increases, extreme variability within the samples is reduced, suggesting that the mixture becomes more homogeneous and approaches the Poisson distribution, which is an indicator of ideal random distribution in this context.

Fig. 3 combines the dispersion and distribution of particles at each mixing time. For the 60, 90, and 210-s intervals, particle dispersion is notably greater, with high

Table 2. Statistical data on central tendency and quartiles for moisture values by mixing time

X	Media (%)	Median (%)	Range (%)	Deviation (%)	Q1 (%)	Q3 (%)	IQR* (%)
60	12.61	12.64	0.44	0.11	12.59	12.67	0.08
90	12.62	12.64	0.46	0.13	12.52	12.74	0.22
120	12.28	12.27	0.29	0.07	12.24	12.33	0.09
180	12.41	12.41	0.40	0.11	12.34	12.48	0.14
210	12.63	12.64	0.38	0.13	12.56	12.72	0.16

Note: *IQR: Interquartile range

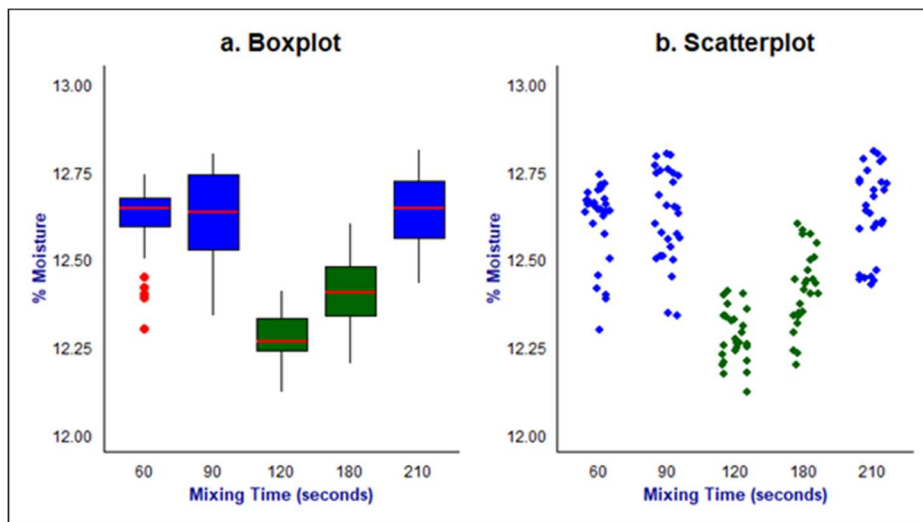


Fig . 4. (a) Box plots and (b) scatter plots of moisture values for each mixing time.

variability characterized by wide box plots and the presence of outliers (particularly at 210 s), which visually confirms the presence of a less homogeneous mixture. This is consistent with the statistical results, where higher CVs and lower p-values reflect an uneven distribution of particles.

In contrast, for mixing times of 120 and 180 s, the particles are distributed more uniformly, with more compact box plots and no outliers. This behavior also correlates with lower CV values and consistency with the Poisson distribution, indicating that these mixing times are the most suitable for achieving homogeneous mixture. The CV increased significantly from 7.55% (180 s) to 15.95% (210 s). Nevertheless, after excluding an outlier identified in Fig. 3(a), the recalculated CV was 10.57%, with a Poisson CV of 8.11% and a p-value of 0.514 (chi-square test). This indicates that although prolonged mixing time contributes the heterogeneity, other additional factors may also be involved.

3.2 Relationship of Mixing Times to the Percentage of Moisture in the Final Product.

In this section, the detailed analysis of the relationship between mixing time and the percentage of moisture in the final product is presented. An EDA was performed, and the results are shown in Table 2. Fig. 4 complements the information shown in Table 2, providing a visual interpretation of the relationship between mixing time and moisture content in the final product. In particular, Fig. 4(b)

clearly highlights the levels of dispersion and presence of outlier identified in Fig. 4(a). It can be observed that intermediate mixing times of 120 and 180 s exhibit the narrowest ranges and the lowest standard deviations. Additionally, their interquartile ranges reflect lower variability in the central distribution of data, suggesting a more uniform mixture.

In contrast, the extreme mixing times of 60 and 210 s exhibit greater variability. In Fig. 4(a), the 60-s time shows the presence of several outliers, indicating a potentially insufficient mixture. The 210-s group, although displaying a median similar to shorter mixing times, presents a wider interquartile range, which may be associated with overmixing effects.

The 90-s time, while having a mean and median comparable to those of 60 and 210 s, stands out for having the largest interquartile range and for the highest standard deviation in the database. This suggests a less uniform mix, with greater variability in moisture values, possibly due to being a suboptimal intermediate duration in this experimental context. These findings are supported by Fig. 4(b), where the data points corresponding to 120 and 180 s are more tightly clustered, reflecting lower dispersion, whereas the 60, 90, and 210-s times show greater vertical spread, indicative of heterogeneity.

Fig. 5 illustrates the moisture distributions across different mixing times, revealing key patterns. At 60 and 90 s, the distributions show multiple peaks, indicating heterogeneity in the samples and suggesting that the mixing

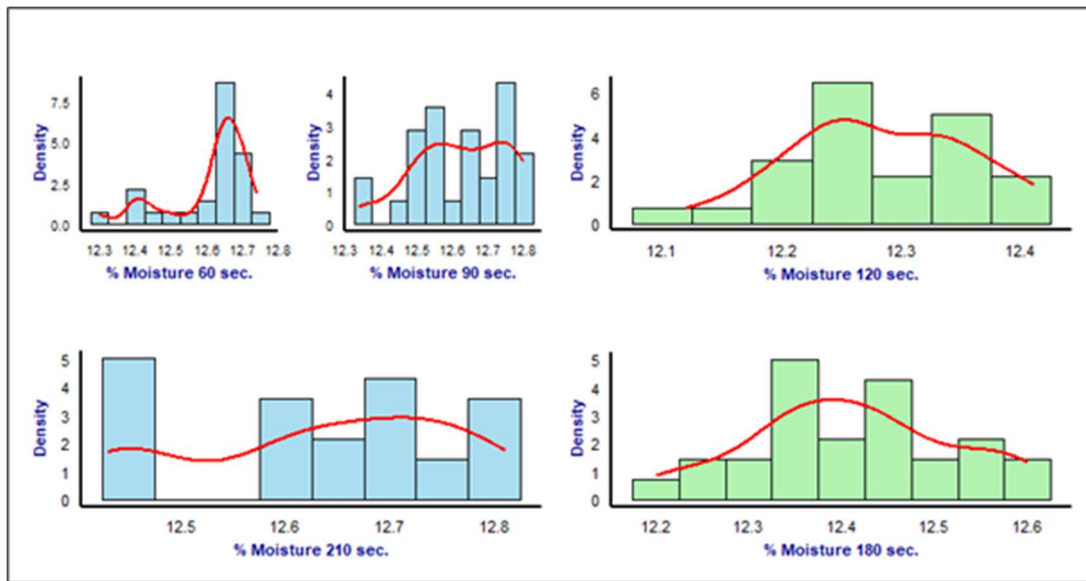


Fig. 5. Distribution and density curve of % moisture by mixing time.

Table 3. Multiple comparisons between mixing time groups using the Dunn test.

Comparison (s)	Z	P. adjusted	Interpretation
120–180	-2.44	0.1487	Not significant: No difference between 120 and 180.
120–210	-7.24	4.46×10^{-12}	Significant: Differences between 120 and 210.
180–210	-4.81	1.55×10^{-5}	Significant: Differences between 180 and 210.
120–60	-6.62	3.52×10^{-10}	Significant: Differences between 120 and 60.
180–60	-4.19	2.82×10^{-4}	Significant: Differences between 180 and 60.
210–60	0.62	1.00	Not significant: No difference between 210 and 60.
120–90	-6.95	3.59×10^{-11}	Significant: Differences between 120 and 90.
180–90	-4.52	6.28×10^{-5}	Significant: Differences between 180 and 90.
210–90	0.29	1.00	Not significant: No difference between 210 and 90.
60–90	-0.33	1.00	Not significant: No difference between 60 and 90

process has not been fully efficient at these intervals. In contrast, the 120 and 180-s times exhibit tighter distributions, indicating more uniform distributions, with a tendency towards greater consistency in the moisture concentration values. Finally, at 210 s, data dispersion increases again, suggesting that overmixing may be affecting the uniformity of moisture in the final product.

Prior to performing the correlation analysis, the normality assumptions of the data were verified using the Shapiro-Wilk test. The results indicated that the data corresponding to the times of 60 s ($p = 0.00021$) and 210 s ($p = 0.0131$) did not follow a normal distribution. The times of 90 s ($p = 0.114$), 120 s ($p = 0.732$), and 180 s ($p = 0.569$) times met the normality assumption. Since the data for the 60 and 210 s did not comply with normality, nonparametric tests were chosen to ensure the validity of the results.

Spearman's nonparametric correlation test was used to evaluate the relationship between mixing time and moisture percentage. The rho correlation coefficient obtained was -0.1245 , 95% CI $[-0.3025, 0.0638]$, with a p -value = 0.1429, indicating that no statistically significant correlation was found between the evaluated variables. The effect size was

small, suggesting that, in general, mixing time does not exhibit a direct and consistent relationship with moisture values in the final product.

To determine potential significant differences in moisture distribution among the different mixing times, the Kruskal-Wallis test was applied, since the data did not meet the assumptions of normality (Shapiro-Wilk test, $p < 0.005$). The results showed statistically significant differences between the groups, with a p -value $< 2.2e^{-16}$, with an effect size of $\eta^2 = 0.599$, indicating a very large effect size and demonstrating that a substantial proportion of the variability in moisture is explained by mixing time. Since significant differences were detected, multiple comparisons between the mixing times were performed using the Dunn's test to adjust the p -values and control for Type I error. The comparisons identified are detailed in Table 3.

The results of the Dunn test with Holm-Bonferroni adjustment revealed significant differences in moisture distribution across several mixing times. Furthermore, Rosenthal's r effect sizes were calculated for each comparison, ranging from 0.20 (small effect) to 0.61 (large effect), providing additional insight into the practical

relevance of the observed differences

In particular, the 120-s mixing time presented statistically significant differences ($p < 0.001$) with 60 ($r = 0.56$, $p = 3.52 \times 10^{-10}$), 90 ($r = 0.59$, $p = 3.59 \times 10^{-11}$) and 210 s ($r = 0.61$, $p = 4.46 \times 10^{-12}$), indicating that this time yields moisture distribution notably different from both shorter times of 60 and 90 s and the longer duration of 210 s. In contrast, no significant differences were found in 120 and 180 s ($r = 0.21$, $p = 0.1487$), suggesting these two mixing times result in similar moisture distributions.

The 210, 60 and 90-s mixing time did not show significant differences among each other ($r \leq 0.05$, $p = 1.00$ in all cases), indicating a non-homogenous behavior in moisture distribution for these treatments. Lastly, the 180-s time showed significant differences from 60 s ($r = 0.35$, $p = 2.82 \times 10^{-4}$) and 90 s ($r = 0.38$, $p = 6.28 \times 10^{-5}$), but not from 120 s, reinforcing the distinct behavior of the latter interval.

4. DISCUSSION

4.1 Determination of optimum mixing time

The results obtained in this research reinforce the relevance of the CV as an essential indicator for evaluating the mix homogeneity, as documented in previous studies that underline its importance in the food industry and the feed production (Poholsky et al., 2021; Rubio et al., 2023), which is associated with the quality of the final product (Sakhno et al., 2018). The results of this study, where the optimal mixing times of 120 and 180 s produced CVs below 10%, corroborate this premise and align with the Poisson distribution, which is used to evaluate the mix consistency.

The importance of a low CV lies in its ability to reflect a uniform particle distribution, a crucial factor in feed production. Homogeneity is critical to avoid nutritional deficiencies and improve formulation efficiency. Incomplete mixing is one of the most common issues in feed production and occurs when mixing times are either too short or excessively long.

In line with our findings, Sakhno et al. (2020) reported that prolonged mixing times (120 and 240 s) reduced the CV in pet food (15.87% and 13.67%, respectively), using ferromagnetic tracers similar to those employed in this study. Nevertheless, unlike our results, when mixing times of 120 and 180 s achieved $CV < 10\%$, the values of Sakhno et al. (2020) exceeded industry-accepted threshold, despite being classified as “complete mixes” under GMP + BA2 standards. Both studies agree that increased mixing time enhances uniformity.

This study suggests the presence of an optimal mixing time around 180 s, where the minimal CV was achieved (7.55%), followed by a decline in homogeneity when the time was extended to 210 s. Comparatively, Rocha et al. (2022) reported a more pronounced reduction (49.5% at 30 s vs 5.4% at 120 s), although both studies align in observing an asymptotic improvement in homogeneity with increasing mixing times and a practical limit to CV reduction (~5%–

8%). The differences in absolute values (with initial CVs being 2–3 times lower in our study) may be attributed to improved mixer design or more standardized sampling protocols. The statistical analysis ($\chi^2 = 182.69$ –380841; $p < 0.0005$) supports these trends, although it also indicates that not all incremental time increases lead to statistically significant improvements ($p > 0.05$ for some comparisons).

A relevant aspect is that Rocha et al. (2022) did not evaluate mixing times beyond 120 s, which limits the understanding of potential overmixing effects, such as particle segregation or nutrient degradation, which might arise with prolonged mixing. Our results at extended times (180 s) an asymptotic trend, with marginal improvements in homogeneity beyond certain critical points, as observed at 210 s, where the adjusted CV reached 10.57%.

On the other hand, Bratishko et al. (2020) provide a complementary approach by using heterogeneity coefficients (v_m), interpreted as follows: $v < 5\%$ for excellent mixtures, $5\% \leq v < 10\%$ for good mixtures, and $v \geq 20\%$ for unsatisfactory mixtures. Their research observed that mixing times exceeding 180 s were necessary to achieve homogeneous mixtures ($v_m \approx 7.56\%$) under specific conditions of hay content ($< 20\%$). This finding underscores the importance of mixing duration in achieving a uniform particle distribution. It also highlights that influence of other factors, such as ingredient type (in this case, hay) and moisture content, play a significant role in homogeneity.

Adusei-Bonsu et al. (2021) performed a comparative evaluation of different mixer types (horizontal and vertical) and their mix times. Horizontal mixers achieved CV of 7.19% with mixing times of 1.5 to 10 min, whereas vertical mixers underperformed, with CVs ranging from 10.30% to 18.05% and mixing times of 15 to 30 min. These results highlight the significant impact of the type of technology used on mixing efficiency. Mixing technology and equipment designs are key factors affecting particle distribution and mixture quality, as evidenced by the results of this study, where specific technology was used to optimize mixing times and achieve acceptable homogeneity. Rubio et al. (2023 citing Stark, C. and M. Saensukjaroenphon, 2017) mention that recommended that mixing time for broilers during the growth stage ranges from 3 to 5 min (180 to 300 s) to maintain nutrient homogeneity and comply with regulations regarding feed manufacture. This recommendation aligns with the mixing times of 180 and 210 s in the present study, which yielded CVs of 7.55% and 15.95%, respectively.

The results in this study showed a significant increase of CV from 180 (7.55%) to 210 s (15.95%). Upon excluding an outlier, CV adjusted was from 10.57%, with a p-value of 0.514 (Poisson distribution). This pattern is consistent with the findings reported by Rubio et al. (2023), who observed that mixing uniformity may decrease with prolonged mixing times. Such effects may be attributed to overmixing or particle segregation, possibly due to differences in particle size or density.

Çiftci and Ercan (2003) reported $CV < 10\%$ at a mixing time of 225 s, but under dietary formulations and analytical methods. This highlights the fact that the optimal mixing time is not universal but rather depends on the specific experimental context. According to Poholsky et al. (2021), nutrient segregation in broiler diets may be exacerbated by elevated CV during mixing. Feed particle segregation may lead to an even distribution of nutrients. Meanwhile Adusei-Bonsu et al. (2021) highlighted ingredients with contrasting densities (e.g., minerals vs. meals) tend to separate during mixing, which might explain the heterogeneity observed at 210 s.

The literature identifies multiple variables that influence the CV beyond mixing time. Factors such as particle size, shape, density, and the order of ingredient addition, are critical for mix quality (Astanakulov et al., 2024). Additionally, the type of mixer, its maintenance condition, and cleanliness significantly impact uniformity (Cella et al., 2021). Furthermore, diet formulation, the sampling method, and the fact that each mixer analysis is unique are also relevant considerations (Clark et al., 2007).

4.2 Relationship between Mixing Times and the Moisture Percentage in the Final Product.

The influence of moisture on pellet quality is a widely documented factor. According to Chuah (2021), adding moisture through water in the mixer or steam in the conditioner significantly improves the Pellet Durability Index (PDI), with differences observed between the two methods ($p < 0.0001$). However, while water in the mixer reduces the mill energy consumption, it cannot match the impact of steam in terms of pellet physical quality. In line with these findings, our research demonstrates that intermediate mixing times (120–180 s) can optimize moisture distribution, achieving CVs below 10%, suggesting a positive interaction between mixing time and product quality. Nonetheless, Chuah (2021) emphasizes that uneven hydration can compromise pellet structure and durability, underscoring the need for improved control mechanisms at all stages of the process. These results highlight the importance of precise control to avoid thermal variations that could negatively impact the final quality of the feed.

The finding that intermediate mixing times (120 and 180 s) result in greater homogeneity aligns with previous studies emphasizing the importance of adequate mixing time for the uniform distribution of components in the final product. In this regard, our results complement those of Zambrano et al. (2022), who found that factors such as initial moisture content and production operating conditions influence the microstructural properties of the product. Although the authors used advanced technologies such as micro-CT to analyze product texture, our experimental focus on mixing time underlines the relevance of controlling operational parameters in a more accessible and direct manner. This finding underscores the importance of rigorous mixing time

control as an effective tool to improve the quality of the final product by ensuring a more homogeneous moisture distribution, which is fundamental for product consistency and durability.

Oliveira et al. (2022) demonstrated that the addition of 850 μm particles and moisture levels of 1.6% improves digestibility and metabolizable energy in corn-based feeds. This study highlights the relationship between particle size, moisture, and mixing efficiency. Although our research did not focus on the influence of particle size, we observed that controlling mixing time influences moisture homogeneity, which may have similar effects on process efficiency. These results broaden the understanding that, in addition to optimization of initial conditions, precise control of mixing times is a key factor in ensuring homogeneous mixtures and improving the nutritional quality of the final product.

The research by Wecker et al. (2020), which found a significant increase in feed moisture content when modifying the conditioning temperature, provides an interesting contrast to our findings. In their study, increasing the conditioning temperature (from 62.78°C to 87.7°C) increased moisture by up to 17.3%, which improved the PDI of 91.1%. Although no changes in conditioning temperature were evaluated in our study, the optimal mixing times identified in our research underscore that moisture content homogeneity can also be achieved through adjustments in mixing time, without modifying the thermal conditions of the process. This finding highlights the operational flexibility in moisture control, suggesting that mixing time can be an effective standalone tool to improve the quality and durability of the final product.

On the other hand, Vakili (2023) demonstrated that the use of fine particles (6 mm) and the addition of moisture ranging from 2.5% and 5%, combined with conditioning temperatures of 75°C to 85°C, improved the physical quality of pellets, including their durability. Although our research did not focus on conditioning temperature or particle size, our results reinforce the idea that homogeneity in moisture distribution can be achieved without additional thermal adjustments. This finding opens new operational possibilities for improving product quality, suggesting that controlling mixing time may be sufficient to achieve homogeneous moisture distribution without relying on other variables such as temperature or particle size.

Additionally, the results of Budak and Bilgeçli (2024) show that adding organic acids and surfactants in the mixing process increases moisture retention and improves energy efficiency. Although these additives were not used in our study, the results show that moisture variability can be significantly reduced through appropriate control of the mixing time. This emphasizes that, even in the absence of additives, optimizing the mixing process through time adjustments can be an effective strategy for improving moisture homogeneity in the final product.

In terms of nutritional and digestive effects, Kiarie and Mills (2019) found that particle size and hydrothermal temperatures between 75°C and 95°C influence feed quality

and gastric pH, affecting digestibility and nutrient utilization. Although our study did not address these factors, the results suggest that improved moisture homogeneity could positively impact particle interaction with digestive enzymes, potentially optimizing the nutritional quality of the final product. This highlights the importance of integrating mixing strategies with precise particle size and temperature controls in later production phases.

The findings of this research demonstrate that, although the relationship between mixing time and moisture percentage is not directly proportional, mixing time significantly influences the moisture homogeneity in the final product. The results obtained are consistent with previous studies and open new perspectives on how mixing times can be adjusted to optimize the quality and efficiency of industrial production processes. The ability to control moisture distribution by adjusting mixing time represents an effective operational strategy that can be applied to improve the feed quality and other industrial products.

5. CONCLUSION

The study comprehensively conducted evaluated the influence of mixing time on the homogeneity and moisture percentage of broiler feed using ferromagnetic microtracers and advanced statistical analysis. The results showed that intermediate mixing time at 180 s is the most effective to achieve homogenous mixtures, with the lowest CV and consistent with Poisson distribution. Spearman's correlation did not show a direct and significant relationship between mixing time and moisture percentage. However, the Kruskal-Wallis and Dunn's tests revealed that 120 s did not show significant differences at 180 s ($p = 0.1487$), suggesting that both times produce similar moisture distributions. Therefore, 180 s can be selected as the optimal mixing time without compromising product quality in terms of moisture-related degradation.

These findings highlight that optimization does not entail a single universal mixing time, but rather a balance between quality parameters and efficiency. The flexibility in selecting either 120 or 180 s allows adaptation to the specific needs of the plant, thereby supporting the sustainability and competitiveness of the poultry industry. This study provides a robust scientific basis for optimizing industrial processes, improving product quality and reducing operating costs, with direct implications for sustainability and efficiency in the poultry industry.

DECLARATION OF COMPETING INTEREST

The authors declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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